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The environmental impact of container pipeline transport compared to road transport. Case study in the Antwerp Harbor region and some general extrapolations

Johan Braet

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Abstract
Purpose Increasing mobility demands and growing industrial tissue come with a burden for the environment. Inventive solutions are necessary to address this challenge. This paper compares the environmental impact of two alternative container transportation methods over a 25-year time period for a specific trajectory and transport volume in the Antwerp harbor. One is a pipeline concept; the other a road concept to link the Deurganck dock with the right bank in order to transport 2 million containers per year.
Materials and methods With a detailed bill of material and the use of the Ecolizer method, a Monte Carlo simulation was performed to calculate the environmental impact in terms of ECOPOINTS on a life cycle perspective.
Results and discussion The results remark that in 94% of the cases the pipeline concept has less than half of the environmental impact of the road concept. Furthermore, in both concepts the operational phase is the largest contributor to the total environmental impact.
Conclusions The pipeline concept results suggest a much lower total environmental impact over a road concept if a large enough volume of containers can effectively be transported. Some considerations have to be given to the used electricity mix, the applied impact assessment method and the case specificities.

Keywords Antwerp Harbor · Ecolizer · Environmental impact · Life cycle assessment · Pipeline transport · Road transport

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J. Braet (✉)
Department of Environment, Technology and Technology Management, Faculty of Applied Economics,
University of Antwerp,
Prinsstraat 13,
2000 Antwerp, Belgium
e-mail: johan.braet@ua.ac.be

1 Introduction

Mobility is certainly one of the current major issues in society. Increasing mobility demands and growing industrial tissue come with a burden for the environment. (EU 2001) This may be seen as a "no end" street a "contradictio in terminis"; so inventive solutions are necessary (Winkelmans 2009).

Besides the already discussed and applied intermodal transport and modal shifts such as lorry to train or lorry to ships (Frémont and Franc 2010; Kreutzberger et al. 2006; Rich et al. 2009), other more sophisticated systems are proposed, and in some cases in use, such as multimodal transport terminals (Schönharting et al. 2003), or transport by using double-stack containers (Bontrager 1993). In spite of efforts, most of these new approaches seem to suffer some major problems as the breakthrough is not happening or all teals not at the pace one expected (Winkelmans 2008).

Transport via pipelines or tubes may be a basic solution where increase of mobility can go together with lower impact on the environment as claimed already by the believers (Vernimmen et al. 2007). The aim of this paper is to bring a bottom-line comparison between two traffic modes in a very specific application based on a method recognized by the Flemish government for assessing environmental impacts (Vlaamse Overheid 2011).

This paper reports environmental impact calculations on a specific case study with an extrapolation potential towards general applicability of pipeline concepts for transport of goods.

2 Aim, functional unit, research questions, and data sources

2.1 Aim

The goal of this research was to analyze on the basis of a specific example whether the underground piping transport for container traffic has a lower environmental impact than the same traffic organized by road transport using lorries.

2.2 Functional unit

The functional unit used in this paper is a complete transport concept able to transport two million containers per year (one million in each direction) in the Antwerp harbor from the right bank to the left and vice versa over a time period of 25 years.

The first transport concept is a specific pipeline case and trajectory as developed by the Belgian company Denys NV. This company is specialized in underground pipeline constructions (Denys 2010). The specific application in the Antwerp harbor is intended for serving the new Deurganck dock put in activity in 2005. As the city of Antwerp and the Flemish Government plan to build another dock of the same type at the same left bank of the Scheldt, the extra needed hinterland transport threatens to block all road traffic in the region. As an alternative to the pipeline concept, I use a comparable road concept (transport with lorries).

2.3 Research questions

The research questions can be summarized as:

(a) Is the pipeline system as proposed by Denys having lower environmental impact than the road concept? Is this difference to be considered as significant[1] ?
(b) In a life cycle perspective approach, which of the phases[2] of the pipeline concept has the highest contribution to the environmental impact and consequently should be addressed with priority for further decreasing the environmental impact of the pipeline concept?
(c) Can some of the conclusions be extrapolated to general conclusions on the applicability of the pipeline concept as an alternative for transport of goods?

[1] Significance is determined by the author as a p value of less than 0.01 over all simulation scenarios and a difference between the average values of no less than 25% based on the lowest average value.
[2] I distinguished three major phases in the cradle-to-grave approach based on Curran (2006): construction, operational phase (use), end-of-life phase.

2.4 Data sources

For both concepts I relied on expert interviews to obtain an adequate understanding for a process analysis in terms of environmental impact and a detailed bill of material for those processes deemed significant. The R&D director at Denys NV (Delbaere 2009) and the Benelux Pipeline Guild “Buisleidingen Industrie Gilde” (BIG) (BIG 2010) provided the information regarding the pipeline concept.

The experts involved in the road concept were a site manager of WEGEBO (Bogaerts 2009) and an official of the Flemish government (Hermans 2010).

3 Methodology

3.1 Life cycle assessment-based ECOPOINTS method

I used the Ecolizer[3] method (in the remaining of the text it will be referred to as “ECOLIZER”) as proliferated by OVAM (the Flemish Public Organization for waste management) to assess environmental impacts. ECOLIZER contains ECOPOINTS for several materials, material processes, transportation modes, energy production methods, recycling, and waste disposal processes. These numbers reflect a relatively recent (2009) view on the degree of environmental impact of these materials, processes, etc. The higher the ECOPOINTS, the higher the environmental impact.

The first version of ECOLIZER was created in 2005 and was largely based on the Eco-indicator 99 method developed by PRé-consultants BV in the Netherlands.[4] Four years later, an updated version (2.0) was published which is based on the ecoinvent database 2.0 and the more extensive ReCiPe method (Goedkoop et al. 2009).

ECOLIZER provides a lean and mean approach for a rough estimate of the environmental impact of a product or process. ECOLIZER is best used in a comparative mode and firm conclusions are only allowed when significant differences are monitored between the two or more items compared.

I used ECOLIZER for two reasons: first, it is quick and cheap, though limitations are known; second, it can be highlighting the need for some more in depth study, certainly when the ECOPOINTS of two cases in a comparison point out to be close to one another. Indeed, due to the intrinsic inaccuracy of ECOLIZER, the statements are only relevant in those cases where the differences in ECOPOINTS between the two cases are significant.

[3] http://www.ovam.be/
[4] http://www.pre.nl/

3.2 Statistical data handling (data uncertainty)

As I compared two concepts that were not yet put in practice (i.e., uncertainty about the actual implementation) and due the inherent variability of the parameters impacting both concepts, I decided to have a stochastic approach (Coulon et al. 1997; Hubbard 2009). The variation of all major parameters impacting the analysis was evaluated and taken into account using a Monte Carlo simulation.

Two assumptions were made regarding this type of statistical data handling. First, I assumed that the normal probability density function governed all parameters considered. Second, no correlations between parameters were considered.

4 Concept details

4.1 The pipeline concept of Denys NV/SA

The specific embedment of the pipeline concept can be found in Fig. 1. The length of the proposed closed loop is about 20.8 km of which about 13.3 km will be actually underground pipeline. The rest of the trajectory will be open slots for up- and unloading the containers at various points (Delbaere 2009).

Although it is proven that pipelines have lifetimes longer than 25 years (Delbaere 2009; BIG 2010), I limited it to 25 years.

The containers are put on the wagons using one of the 24 terminals. The process is fully automated as the chain with 350 wagons runs with a constant speed of about 6.85 km per hour. The containers follow the track of the rails until they meet the terminal at the right bank, ready for unloading and transferring to another traffic mode. Motors are considered to run all day and the replacement is foreseen to take place every two years. Total installed electrical power is between 5 and 6 MW, sufficient—in this specific case—to power the chain when maximally loaded. Maintenance and repair are based on existing sector experience (Delbaere 2009).

For ease of calculation, I limited the disposal phase to two possibilities: recycling or dumping the materials on a waste disposal discharge place. The recycling rates were based on sector information. An overview of the main materials and assumptions made in the pipeline concept is shown in Table 1.

4.2 The concept of road transport

I developed a road concept that could serve the same goal and enable the same transport capacity. The length of this road concept is 18 km. I assumed no tunnel or bridge constructions along this road. These more special types of road construction make the analysis overly complex. I did take the specific situation of the left bank of the Antwerp harbor into account, which needs extra foundation due to the soil type.

In the construction phase, excavations and foundations, sewerage systems as well as different finishing layers were considered based on the specific underground in the Antwerp region (Hermans 2010). On the right bank of the Scheldt it is possible to work with reinforced concrete as finishing layer, on the left bank side it is not, due to the specific underground conditions there. For the left bank side asphalt is chosen as finishing layer. The sector taught me that reinforced concrete has a lifetime of about 25 years

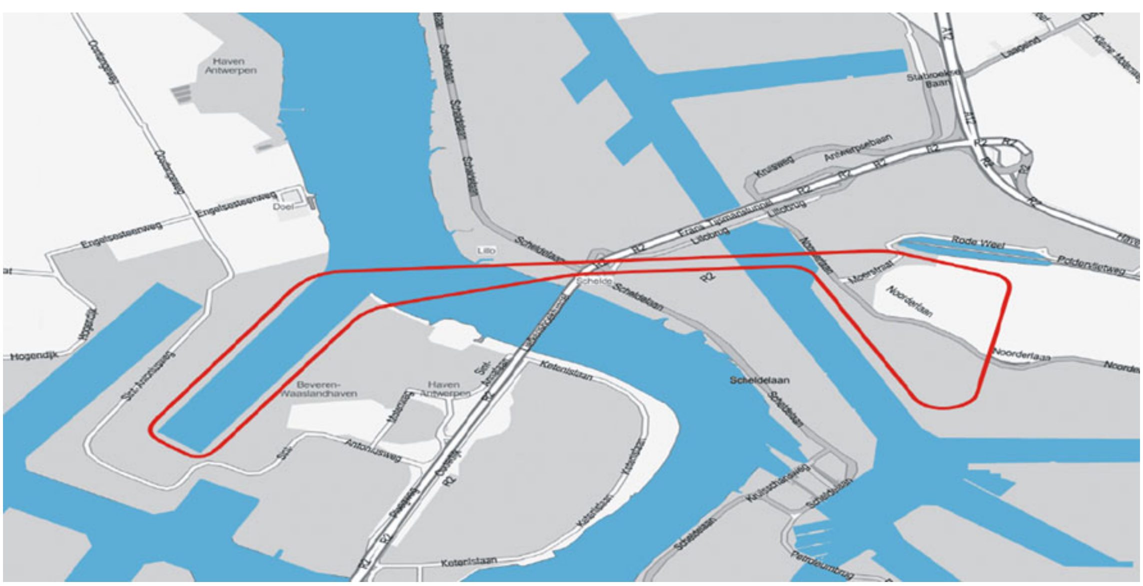

Fig. 1 Embedment of the pipeline track in the Antwerp Harbor as developed by the company Denys

Table 1 A review list of the main sub-processes, materials, and assumptions used for the pipeline concept

		Construction phase		Operational phase		Disposal phase	
	Unit	Min 90% CI	Max 90% CI	Min 90% CI	Max 90% CI	Min 90% CI	Max 90% CI
Construction tunnel							
Steel drilling machine	tonne	580	770				
Electricity (Belgian mix)	MWh	14,300	24,500				
Excavated ground	tonne	450,000	525,000				
Concrete tubes, work pits, open slot	m³	184,550	240,100				
Steel tubes, work pits, open slot	tonne	24,800	28,900				
Replacement period tubes	years				>25		
Recycle rate drilling machine	%					90	100
Recycle rate work pits	%					5	10
Recycle rate tubes	%						0
Recycle rate open slot	%					50	100
24 Terminals							
Steel	tonne	660	830				
Electricity (Belgian Mix)	MWh			505,000	930,000		
Replacement period	years				5		
Recycle rate	%						100
Rails							
Steel	tonne	2,400	2,500				
Replacement period	years			5	10		
Recycle rate	%					50	100
Chain							
Steel	tonne	630	1,000				
Replacement period	years			3	5		
Recycle rate	%						100
20 Motors							
Concrete	m³	372	444				
Steel	tonne	93	116				
Copper	tonne	5	7				
Electricity (Belgian Mix)	MWh			779,000	1,025,000		
Replacement period	years				2		
Recycle rate steel and concrete	%					80	100
Recycle rate copper	%						100
350 Wagons							
Steel	tonne	3,600	4,300				
Replacement period	years				6		
Recycle rate steel	%						60

Main as defined in terms of environmental impact

Data organized per life cycle phase. Constituted on the basis of expert interviews with Denys (Delbaere 2009) and BIG (BIG 2010)

without maintenance, while asphalt requires replacement after 15 years (Bogaerts 2009). Other maintenance data is based on expert knowledge (Pecqueur 2011).

In the operational phase, I assume that containers are immediately placed on >32-t lorries compliant with the EUR4 norm (EC 2002). Yearly transport distance and expected lifetime of these lorries are based on expert knowledge. By assuming the number of trips that return empty to be between 30% and 50%, the corresponding number of lorries needed is between 340 and 380.

For ease of calculations I limited the disposal phase to two possibilities: recycling or dumping the materials on a waste disposal discharge place. The recycling rates are based on sector information. An overview of the main materials and assumptions made in the road concept is shown in Table 2.

Table 2 A review list of the main sub-processes, materials, and assumptions used for the road concept

	Unit	Construction phase		Operational phase		Disposal phase	
		Min 90% CI	Max 90% CI	Min 90% CI	Max 90% CI	Min 90% CI	Max 90% CI
Foundation and finishing layers							
Excavated ground	tonne	440,000	740,000				
Gravel	tonne	250,000	290,000				
Cement	tonne	2,400	4,000				
Asphalt	tonne	68,000	110,000				
Concrete	m³	23,000	36,000				
Steel	tonne	1,300	2,000				
Replacement period asphalt finishing layer	years				15		
Recycle rate gravel, cement, concrete, steel	%						100
Recycle rate asphalt	%					0	20
Sewerage							
Excavated ground	tonne	250,000	260,000				
Cement	tonne	3,800	3,900				
Cast iron	tonne	150	160				
Concrete	m³	7,800	8,000				
Recycle rate cast iron, concrete, cement	%					60	85
Barriers							
Concrete	m³	12,000	28,000				
Recycle rate concrete	%						100
Lightning							
Electricity (Belgian Mix)	MWh			17,000	18,000		
Lorries							
Rubber	tonne	210	240				
Steel	tonne	4,500	5,000				
Aluminum	tonne	38	43				
Yearly mileage per lorry	km				125,000		
Replacement period tires	years				1.5		
Replacement period lorries	years				6		
Percentage empty return trips	%			30	50		
Recycle rate rubber	%						0
Recycle rate steel, aluminum	%						100

Data organized per life cycle phase. Constituted on the basis of expert interviews with Wegebo NV (Bogaerts 2009), M. Pecqueur (Pecqueur 2011) and the Flemish government (Hermans 2010)

5 Assumptions

I addressed the research questions within the limitations of some assumptions: (1) some differences between the two modes under comparison were considered to be negligible; (2) the contribution of some of the elements to the environmental impact were—based on experience or previous calculations—negligible compared to the total contribution or (3) the contribution of some of the elements to the environmental impact was—based on experience or previous calculations—negligible compared to other elements in the process. The concept “negligible” was being interpreted as less than 1% of the total environmental impact expressed in ECOPOINTS. Some of these exclusions were determined by iterative calculations. One exception to this rule was the assumption that I did not take tunnel or bridge constructions into account for the road concepts for simplification reasons.

Besides assumptions related to the scope and comparison of both concepts, I also had to make some assumptions related to ECOLIZER: first, not all materials are assigned ECOPOINTS, implying that I had to assign ECOPOINTS of a related material; second, I also had to adapt some of the ECOPOINT to our specific case, because the underlying assumptions for deriving the score were not fulfilled in this study. Because I do not assume that every lorry returns

empty for every trip, I made an ECOPOINTS scale for transport on the basis of interpolation.

An overview of the main assumptions can be found in the Electronic supplementary material.

Chosen timeframe of 25 years Although pipelines generally have a longer lifetime than 25 years, I fixed the timeframe at 25 years (equal to the lifetime of reinforced concrete, which is the main finishing layer in the road concept) mainly for three reasons. First, the preliminary results showed that the operational phase was contributing the bulk of the environmental impact and not the construction phase. Second, the statistical method used, is based on homoskedasticity of the underlying data, an assumption that would no longer be valid when considering a longer lifetime for the calculation; hence, the use of heteroskedastic GARCH-models would be more appropriate, putting the mathematical complexity out of the scope of this publication. Third, in terms of this comparison between the two concepts, the environmental performance of combustions engines as well as the production of electricity will certainly improve in the next decades; e.g., by using hydrogen in combustion engines. However, given the current status of these technologies, up to now, no statistically reliable data are available to substantiate the predictions of the eventual performance for a longer period than 15 to 25 years.

6 Results

The headlines of the Monte Carlo simulation results for the ECOPOINTS for the two concepts are depicted in Table 3. The total environmental impact for transporting two million containers per year is in favor of the pipeline concept: the average of the distributions is about 2.8 times apart over the chosen time frame of 25 years.

For both concepts the largest relative contribution to the total environmental impact is the operational phase; as far as the operational phase in concerned, the road concept has three times more impact than the pipeline concept (comparing the averages). The pipeline concept has, for the construction phase, twice the impact of the road concept.

Table 3 Resulting ECOPOINTS: average and standard deviation for the different phases of the pipeline concept and the road transport concept

Item/ECOPOINTS[a]	Road transport	Pipeline transport
Construction phase	5.4 (0.1)	11.0 (0.4)
Operational phase	160 (8)	50 (4)
Disposal phase	−2.7 (0.4)	−2.6 (0.1)
Totals	163 (8)	59 (4)

[a] Numbers are expressed in 10^6 ECOPOINTS

The disposal phase appears to have about the same impact for both concepts.

The results of the Monte Carlo simulation for the ECOPOINTS corresponding to the total environmental impact of both concepts are depicted in the histograms of Fig. 2. The variation on the environmental impact is a result of the inherent variation of the underlying parameters.

Figure 2 shows for both concepts a significant variation in terms of expected environmental impact. None of the more than 5,000 Monte Carlo scenarios favors the road concept over the pipeline concept in terms of total environmental impact ($p<<0.01$).

6.1 Construction phase

In Fig. 3, the main sub-processes contributing to the environmental impact in the construction phase are shown for both concepts. For the pipeline concept, the production and placement of the tubes accounts for half the total environmental impact in this phase. The other half is accounted for by the open slots (20%), the drilling machine (11%), the work pits (8%), the wagons (6%), and several smaller contributors (total of 5%)

The road concept's environmental impact in the construction phase is explained by fewer sub-processes. Almost 70% of the total environmental impact in this phase is accounted for by the foundation and finishing layer (including the hard shoulder). Only about 13% is accounted for by the production of the lorries. The remaining 17% is explained by the sewerage sub-process (11%) and the barriers (6%).

6.2 Operational phase

Figure 4 depicts the main sub-processes contributing to the environmental impact in the operational phase for both concepts. For the pipeline concept, two sub-processes

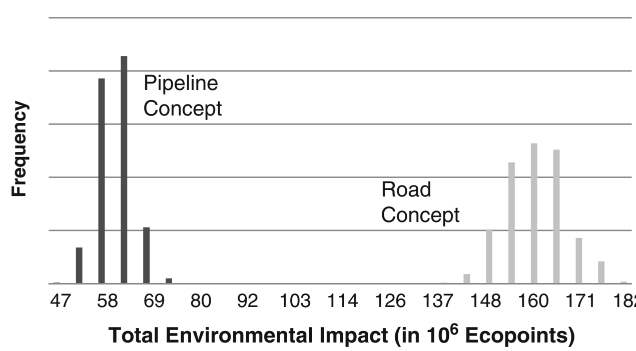

Fig. 2 Histogram of ECOPOINTS (determined by Monte Carlo simulation and ECOLIZER) concerning total environmental impact of both the pipeline and road concept. The frequencies are expressed in relative units

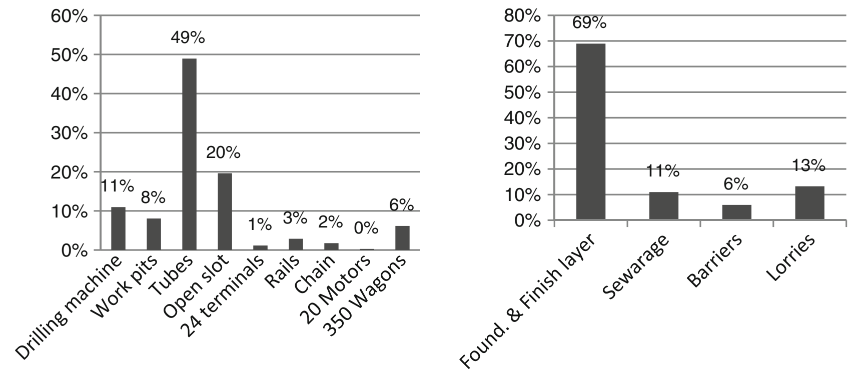

Fig. 3 Relative impact of sub-processes expressed as percentages of the total environmental impact for the construction phase of pipeline concept (*left*) and road concept (*right*)

account for 91% (motors 50%; terminals 41%). Their contributions are mainly explained by the electricity use needed to move the chain and up- and unload the containers. The replacement of materials appears to have a small contribution.

The road concept's environmental impact in this phase is for 96% attributable to the diesel consumption of the lorries. A 3% is attributable to the replacement of tires and lorries; a negligible 1% can be attributed to the maintenance of the road.

6.3 Disposal phase

Figure 5 depicts the main sub-process contributions to the environmental impact in the disposal phase for both concepts. For the pipeline concept, a number of sub-processes significantly contribute to the total environmental impact of the phase. The tubes contribute with positive ECOPOINTS to the disposal phase (26% of the eventual total ECOPOINTS for this phase). The disposal phase as a whole comes with a negative total of ECOPOINTS, causing a mitigating effect on the overall positive ECOPOINTS of the entire concept. Those sub-processes of the disposal phase, however, that do cause positive ECOPOINTS lower this mitigating effect. The tubes are considered to be “lost” in this study because the depth they're put at is too important to make extraction and recycling attractive.

The environmental impact of the road concept in the disposal phase is for 78% attributable to the recycling of the materials used in a lorry. The recycling of the different road layers accounts for 16%, whereas the sewerage and barriers account for, respectively, 4% and 1%.

6.4 Sensitivity analysis

In a final research stage some sensitivity checks were performed to see: (1) if the main result, i.e., *the pipeline concept has a lower environmental impact than the road concept*, was confirmed; and (2) how the average environmental impact ratio between both concepts changed, i.e., *the total environmental impact of the road concept divided by the total environmental impact of the pipeline concept*.

First, the used method was altered to see whether or not ECOLIZER provides robust results. Second the assumption of the Belgian electricity mix was altered to see the effect of using another electricity mix on the result. Third, the level of *environmental impact for the lorry* within the operational phase of the road concept was determined, that would hypothetically be needed to achieve a break-even between the two concepts.

6.4.1 Alternative impact assessment methods

The ReCiPe Endpoint (H) V1.03/Europe ReCiPe H/H method and the IPCC 2007 GWP 100a V1.02 method were identified as more generally recognized alternative environmental impact assessment methods. The former gives—similar to ECOLIZER—a total environmental im-

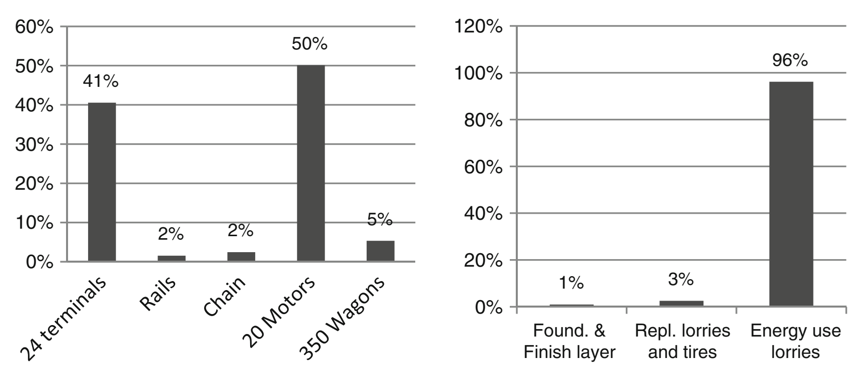

Fig. 4 Relative impact of sub-processes expressed as percentages of the total environmental impact for the operational phase of pipeline concept (*left*) and road concept (*right*)

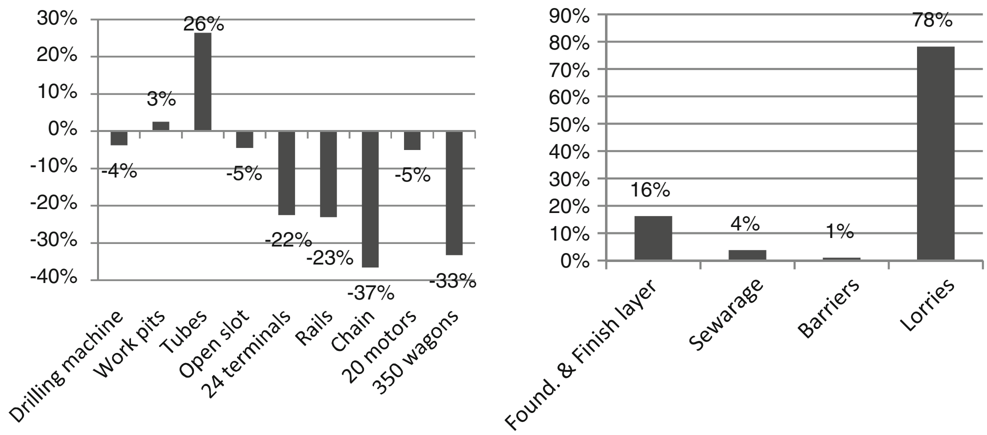

Fig. 5 Relative environmental impact contribution (expressed as percentages of the total impact) of the sub-processes for the disposal phase of pipeline concept (*left*) and road concept (*right*)

pact single score expressed in points, the latter solely calculates the carbon footprint score expressed in kg CO_2 equivalents. The additional calculations were both performed in the SimaPro software version 7.2 based on the ecoinvent database version 2.2.

These two alternative methods enable comparison at smaller differentiation levels, i.e., when differences in outcomes are closer together the discriminative power (significance) of these methods is much better than the one of ECOLIZER.

In Table 4, the difference in average ratio is shown for the different methods. Compared to ECOLIZER a decline in the average ratio of both concepts is noticed.

In the ReCiPe method, a contribution of each environmental impact category to the total impact was calculated as presented in the Fig. 6 below, giving a more detailed insight into the nature of the environmental impact. Only four impact categories significantly contribute to the total environmental impact according to the ReCiPe method. These four categories are *fossil depletion*, *climate change human health*, *climate change ecosystems*, and *particulate matter formation*. These four main categories confirm that the use of electricity and fuel are the most important parameters in the respective concepts. The road concept scores significantly higher for the total impact and consistently comes with higher impact scores for each of these four main categories compared with the pipeline concept.

Table 4 Comparison of the average environmental impact ratio (road concept divided by pipeline concept) and its change compared to ECOLIZER, using other environmental impact assessment methods

Method	Average ratio
ECOLIZER	2.8
ReCiPe	1.8
IPCC GWP 100a	1.6

6.4.2 Alternative electricity mix

In the first part of the study, the Belgian electricity mix was assumed due to the local setting. In the next stage other electricity mixes were assumed in five different energy-scenarios: the continental mix, solely nuclear energy, wind energy, coal energy, and natural gas energy.

The continental electricity mix was used to see if extrapolations of the above results to other European harbors could be made. The use of solely nuclear[5] or wind energy is inspired respectively by the geographical proximity of the nuclear power station at Doel in the Antwerp harbor case and the possibility of building large-scale wind turbines.[6] The coal energy and natural gas power scenarios were calculated to see the impact of CO2-intensive electricity production methods on the conclusion. The scenarios using the continental mix, the nuclear energy, and the coal energy were calculated using the three different environmental impact assessment methods. The wind energy scenario was only calculated with ECOLIZER; the natural gas scenario only with ReCiPe and IPCC GWP 100a. Table 5 shows the results.

Table 5 shows that the difference between both concepts is very sensitive to the type of electricity assumed. The average environmental impact ratio (road concept divided by the pipeline concept) for the three energy scenario's varies from 0.6 to 10. In the coal energy scenario the road concept performs better than the pipeline concept using the ReCiPe or IPCC GWP 100a method. In the natural gas scenario both concepts have an equal environmental impact for all available methods used. In all other electricity production

[5] The nuclear energy scenario is applicable to regions were nuclear power is being used for production of Electricity such as France, Belgium, the UK, and recently Finland.

[6] As most harbors are likely to be situated in areas with important wind fields, the implementation of windmills for electricity production gives an important opportunity contribution to the pipeline concept.

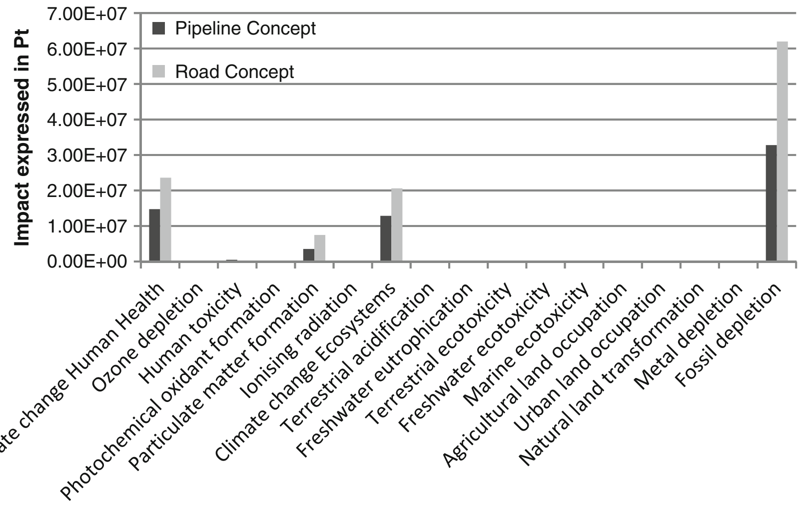

Fig. 6 Specific contribution according to the environmental impact categories determined for both concepts by the ReCiPe method. The impacts are expressed in points (*Pt*)

scenarios the pipeline concepts outperforms the road concept for all available impact assessment methods used.

6.4.3 Projection for the lorry's environmental impact to achieve break-even between the two concepts

The assumed timeframe of 25 years is quite long. As the evolution in terms of environmental impact of road freight transport is difficult to assess, a projection was made to see by how much the current environmental impact of a lorry of >32 tonne, EUR4 has to decrease in order to break-even both concepts for the basic scenario of the Antwerp Harbor and the Belgian electricity mix. The calculation showed that the current impact must drop with a factor of three.

EUR5 lorries do not consume less fuel compared to the EUR4 lorries for equal loads and trajectory conditions (Pecqueur 2011; Delphi 2010) and the major part of the environmental impact of a lorry is linked to its fuel consumption. Consequently most of the emissions are to be expected at an equal level to the current one. A drop in environmental impact of the lorry can thus not be expected in the near future.

Table 5 Comparison of the average environmental impact ratio (road concept divided by pipeline concept) and its relative change compared to ECOLIZER, using three environmental impact assessment methods and applying five different electricity scenarios

Method	Electricity mix	Average ratio
ECOLIZER	Belgian mix	2.8
	Continental mix	1.9
	Nuclear energy	10
	Wind energy	10
	Coal energy	1.05
	Natural gas	NA[a]
ReCiPe	Belgian mix	1.8
	Continental mix	1.2
	Nuclear energy	8
	Coal energy	0.7
	Natural gas	1.0
IPCC GWP 100a	Belgian mix	1.6
	Continental mix	1.1
	Nuclear energy	7.3
	Coal energy	0.6
	Natural gas	1.0

[a] In the Ecolizer 2.0, no value for the electricity production using natural gas is available

7 Conclusions

I made several calculations of the environmental impact of two transport concepts e.g., a pipeline concept versus a road concept, for transporting two million containers per year in a specific setting in the Antwerp Harbor region. Based on two concept maps the life cycle assessment was performed using the ECOLIZER, the ReCiPe, and the IPCC GWP 100a method.

The results show an important difference in terms of average total environmental impact between the two concepts. In the reference case (Antwerp Harbor, Belgian electricity mix and ECOLIZER), the road concept has more than double the environmental impact than the pipeline concept (the minimum factor of two is present in 94% of the simulated Monte Carlo scenario's).

The total environmental impact is mainly determined by the operational phase for both concepts (> 80% for the pipeline concept; > 95% for the road concept). In the construction phase though, the pipeline concept has twice as much environmental impact than the road concept. The difference between both concepts in the construction phase

however would decrease if a longer time frame would be assumed due to the longer lifetime of pipelines. The disposal phase, although having quite optimistic recycling rates, comes with similar impacts for both concepts and does not have a significant impact (less than 2%) on the overall environmental impact.

It must be noted that the difference between both concepts is very sensitive to the electricity mix assumed in the study. Differences were also noted when other environmental impact assessment methods were used. Only in the scenario where the electricity is produced via coal, the conclusion is inversed and in the scenario where the electricity is produced via natural gas both concepts have an equal impact. In the other electricity production scenarios (Belgian mix, European mix, nuclear energy, and wind energy), the pipeline outperforms the road concept with at least a 10% difference (Continental mix, IPCC GWP 100a method) up to a 900% difference (nuclear and wind energy, ECOLIZER). It should be emphasized that a lot of European harbors did already invest or are at the point of investing in windmill parks, in favor of the pipeline concept.

Extrapolation of these conclusions for the pipeline concept can be made to crowded European areas with a large enough container traffic capacity and where electricity is available for the pipeline concept based on production scenario's other than those using coal and natural gas. In these situations the pipeline concept comes with a significantly lower environmental impact than the road concept.

It should be emphasized that in the road concept, no bridges and tunnels were incorporated, favoring the road concept, mainly in the construction phase. Next to that, the average lifetime of a pipeline concept is known to be much longer than 25 years. Hence, a calculation using a longer period would probably favor the pipeline concept, as the relative contribution of the construction phase is moderated inverse linearly with time. On top of that, the projection on 25 years is also inspired by the lack of accurate and reliable data beyond such a timeframe. Consequently, I preferred not to take into account these two aspects.

Next, I note the important upward potential for the pipeline concept when providing the electricity –as the largest contributing factor in the environmental impact of this concept- by using, nuclear power plants or wind mills, resulting in a significantly lower environmental impact than the Belgian electricity mix: the impact ratio between both concepts increases from 2.8 (reference case using ECOLIZER) to 10 (nuclear or wind energy using ECOLIZER).

Finally, I want to point to the extra upward potential of using the energy of downwards going containers to pull some other upwards at the other end of the pipeline terminal. This energy recuperation can be substantial, but was not taken into account in this study.

8 Recommendations for further research

I believe extra research on other cases concerning this type of transportation is needed to confirm the extrapolations made in this paper as the country electricity mix could be higher than the continental mix and the impact of the pipeline concept is very sensitive to the type of electricity used.

The road concept could be developed further in detail to incorporate bridges and/or tunnels.

Decision makers would benefit from additional accompanying economic, technical, and social feasibility studies before implementing such large-scale projects, so besides a life cycle assessment approach, these other aspects should be incorporated in a broader investigation.

When modeling this specific case in more detail, further research can focus on specific parameter behavior and potential correlations between parameters. Also, time dependence of some of the parameters could be considered to incorporate time-dependent dynamics of parameters and heteroskedasticity.

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